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CONTROL OF STEEL PLANT SCARFING EMISSIONS USING WET ELECTROSTATIC PRECIPITATORS

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CONTROL OF STEEL PLANT SCARFING EMISSIONS USING WET ELECTROSTATIC PRECIPITATORS

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Washington, DC 20460

SUMMARY

The purpose of scarfing slabs, blooms, and billets is discussed as an introduction to a discussion of the control of emissions from scarfing machines. Some technical design information pertaining to the design of wet electrostatic precipitators is presented, as is the limited amount of information available on the characteristics of scarfing emissions. Operating characteristics are given for several electrostatic precipitators presently in operation.

This report was prepared in response to Item AM-5 of the Protocol of the First Working Meeting of the US/USSR Task Force on Abatement of Air Pollution from the Iron and Steel Industry.

РЕФЕРАТ

Рассматривается значение огневой зачистки слябов, блумов и заготовок в связи с контролем выбросов машины огневой зачистки. Дается техническая информация о конструктивных особенностях мокрых электростатических пылеуловителей, а также ограниченное количество имеющихся данных о характеристиках выбросов при огневой зачистке. Даны рабочие характеристики нескольких электростатических пылеуловителей, применяемых в промышленности.

Отчет представлен согласно с пунктом АМ-5 протокола первого рабочего совещания США/СССР Группы по борьбе с загрязнением атмосферы металлургической прмышленностью.

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I. INTRODUCTION

Scarfing is a process that is used to remove surface defects from steel slabs, blooms, and billets before rolling into semifinished products. A mixture of gaseous fuel and oxygen is used to burn away the defects. The scarfing may be selective on individual defects or it may be over the entire surface of the slab, bloom, or billet. The operation is usually done after the slab, bloom, or billet has been heated to the rolling temperature, but it may also be done on cold steel.

There are about 122 rolling mills of various types in the iron and steel industry of the United States, of which about 59 have scarfing operations for the removal of surface defects. Scrubbers, cyclones, baghouses, water flumes with water sprays, and wet and dry electrostatic precipitators are used to control emissions from about 47 of the scarfing installations.

This Protocol Report discusses the application of wet electrostatic precipitators for the control of emissions from scarfing operations; it is based on available published information and additional information supplied by iron and steel companies.

II. TRENDS IN THE USE OF SURFACE CONDITIONING IN THE UNITED STATES IRON AND STEEL INDUSTRY

Because of the specifications established by customers, many semi-finished steel products must be free of surface defects. Surface conditioning, the designation for the removal of surface defects, is done by hand and machine chipping, by hand and machine grinding, and by hand and automatic scarfing. Until the early 1930's, hand chipping was the only method used for removing surface defects. Chipping machines and grinding machines were developed to make surface conditioning less laborious.

Scarfing is a surface-conditioning method that uses high-purity oxygen to oxidize the surface of the steel and remove the defects. A fuel gas, such as acetylene or natural gas, is used in combination with the oxygen. The purpose of the fuel gas is to ensure that the steel is heated to a sufficiently high temperature, about 870 C (1600 F), so that the high-purity oxygen can react with the steel and remove the surface defects.

In the United States iron and steel industry (excluding most mini-steel mills), about 130 rolling mills of various kinds are used for rolling slabs, blooms, and billets.[1] Automatic scarfing machines are installed in line with the mills to condition the surfaces of slabs and blooms before they enter the first stand of the mill. Billets are usually surface conditioned in the cold state before they are reheated for further rolling. However, some steel companies surface-condition slabs and blooms after they have cooled to ambient temperatures. There are 57 mills, located at various steel plants, with automatic scarfing machines, one plant using scarfing for surface conditioning cold billets, and four plants that use grinding of cold slabs, blooms, and billets as a means of surface conditioning.[2-33] Scarfing is used more than any other method for surface conditioning of steel. In 1935 about 1 percent of the steel produced in the United States was conditioned by scarfing. This increased to about 41 percent in 1968.[34]

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III. AIR-POLLUTION CONTROL FOR SURFACE CONDITIONING OF STEEL

The emissions generated during scarfing are primarily iron oxide fumes. There may be a small amount of carbon dioxide and/or carbon monoxide depending on the carbon content of the steel. The higher the carbon content of the steel, the higher will be the fume emission rate.[35]

Wet and dry electrostatic precipitators, scrubbers, cyclones, baghouses, and water flumes with sprays are used to control emissions from scarfing operations. The distribution of the different types of air-pollution control systems in integrated and nonintegrated steel plants is given in Table 1. A detailed list of the control systems is given in Table 2.[1-32]

The distribution of surface-conditioning installations in Table 1 accounts for 44 installations. There are three additional installations under construction for which detailed information is not as yet available. Of the 47 mills with automatic scarfing machines, 43 have some type of air-pollution control facilities. The remaining four installations use grinders for surface conditioning of the slabs, blooms, and billets.

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TABLE 1. AIR-POLLUTION CONTROL SYSTEMS ON SURFACE-CONDITIONING OPERATIONS

Type of Mill	Dry ESP	Wet ESP	Scrubber	Cyclone	Baghouse	Flumes and Water Spray
Integrated Plants						
Slabbing	2	5	6	1[a]		2
Blooming	1	4	3	1	1[a]	2
Billet	3	2				
Rail	1					
Nonintegrated Plants						
Blooming		1	3		4[b]	
Billet					2[b]	
Total	7	12	12	2	7	4

(a) Grinding used for surface conditioning.
(b) Grinding used for one surface-conditioning installation.

TABLE 2. SURFACE CONDITIONING AIR-POLLUTION CONTROL SYSTEMS IN THE U.S. IRON AND STEEL INDUSTRY

Company & Location	Type of Mill	Annual Capacity		Type of Control Equipment	Gas Flow		References
		tonne	net tons		Nm^3/min	ACFM[a]	
Atlantic Steel Co. Atlanta, Ga.	Blooming	435,456	480,000	Baghouse	(b)		2
Armco Steel Corp. Houston, Texas	Blooming	589,680	650,000	High-energy scrubber	3,996	141,000	3
	Slabbing	1,360,000	1,500,000	High-energy scrubber	2,834	100,000	3
Kansas City, Mo.	Blooming	752,976	830,000	High-energy scrubber	1,304	46,000	3
Middletown, Ohio	Slabbing	2,358,720	2,600,000	High-energy scrubber	2,834	100,000	3
Babcock & Wilcox Co. Koppel, Pa.	Blooming	453,600	500,000	High-energy scrubber	2,550	90,000	4
Bethlehem Steel Corp. Burns Harbor, Ind.	Slabbing	3,084,480	3,400,000	High-energy scrubber	3,117	110,000	5
Johnstown, Pa.	Blooming	2,195,424	2,420,000	High-energy scrubber	2,834	100,000	6,7
	Billet	884,520	975,000	Wet ESP	737	26,000	8,9
Los Angeles, Cal.	Blooming	612,360	675,000	Baghouse	(b)		10
Sparrows Point, Md.	Slabbing	2,721,600	3,000,000	Wet ESP	4,251	150,000	10
	Blooming	2,639,952	2,910,000	Wet ESP	708	25,000	10
Copperweld Corp. Warren, Ohio	Blooming	480,816	530,000	Wet ESP[c]	1,417	50,000	11
Carpenter Technology Corp. Bridgeport, Conn.	Blooming	181,440	200,000	Baghouse[d]			12
CF & I Steel Corp. Pueblo, Colo.	Blooming	563,371	621,000	(c)			12
Crucible Inc. Midland, Pa.	Blooming	1,020,600	1,125,000	(c)			12
Ford Motor Co. Dearborn, Mich.	Slabbing	3,628,800	4,000,000	Water flume & sprays	2,692	95,000	13
Inland Steel Co. East Chicago, Ind.	Blooming	1,134,000	1,250,000	Water flume & sprays	2,550	90,000	14
	Blooming	1,632,960	1,800,000	Water flume & sprays	2,267	80,000	14
	Slabbing	2,903,040	3,200,000	Water flume & sprays	2,834	100,000	14
J & L Steel Corp. Aliquippa, Pa.	Blooming	1,918,728	2,115,000	Wet ESP	3,542	125,000	15
Cleveland, Ohio	Slabbing	2,449,440	2,700,000	Wet ESP	2,834	100,000	15,16
Pittsburgh, Pa.	Blooming	1,647,475	1,816,000	Cyclones	2,834	100,000	15
Jessop Steel Co. Owensboro, Ky.	Blooming	145,152	160,000	Baghouse[d]			17
Kaiser Steel Corp. Fontana, Cal.	Slabbing	2,830,464	3,120,000	Wet ESP	2,324	82,000	18
Lukens Steel Co. Coatesville, Pa.	Plate	521,640	575,000				19
Phoenix Steel Corp. Phoenixville, Pa.	(e)			Venturi scrubber			20

TABLE 2. (Continued)

Company & Location	Type of Mill	Annual Capacity, tonne	Annual Capacity, net tons	Type of Control Equipment	Gas Flow, Nm^3/min	Gas Flow, ACFM(a)	References
Republic Steel Corp.							
Buffalo, N.Y.	Blooming	781,099	861,000	Wet ESP	1,700	60,000	21
Cleveland, Ohio	Blooming	925,344	1,020,000	Wet ESP	2,343	75,000	22
	Slabbing	2,574,634	2,838,000	Wet ESP	2,834	100,000	22
	Billet	635,040	700,000	Wet ESP	1,275	45,000	22
Youngstown, Ohio	Blooming	1,584,878	1,747,000	Baghouse(d)	1,417	50,000	23
Roblin Steel Co.							
Dunkirk, N.Y.	(f)			Baghouse(d)			24
Timken Co.							
Canton, Ohio	(g)	535,248	590,000	Baghouse	5,951	210,000	25,26
United States Steel Corp.							
Braddock, Pa.	Slabbing	2,268,000	2,500,000	Scrubber			27
Duquesne, Pa.	Slabbing	1,496,880	1,650,000	Wet ESP	2,834	100,000	27
Fairless Hills, Pa.	Blooming	1,542,240	1,700,000	ESP(g)	2,343	75,000	27,28
	Slabbing	2,630,880	2,900,000	ESP(g)	3,259	115,000	27
Gary, Ind.	Slabbing	2,558,304	2,820,000	ESP	2,692	95,000	29
	Billet	1,088,640	1,200,000	ESP	1,757	62,000	29
	Rail	618,710	682,000	ESP	879	31,000	29
	Bar	453,600	500,000	ESP	1,757	62,000	29
	Bar	186,883	206,000	ESP	1,757	62,000	29
Homestead, Pa.	Slabbing	2,792,362	3,078,000	Multi-cyclones(d)	232	8,200	30
W-P Steel Corp.							
Steubenville, Ohio	Slabbing	1,385,294	1,527,000	Low-pressure scrubber			3
Y.S. & T Co.							
East Chicago, Ind.	Slabbing	2,363,348	2,604,000	High-energy scrubber	2,834	100,000	32
Campbell, Ohio	Blooming	1,545,869	1,704,000	High-energy scrubber	2,834	100,000	32

(a) ACFM - actual cubic feet per minute.
(b) Scarfing emissions are exhausted to a common baghouse also controlling electric-arc melting-furnace emissions.
(c) Under construction.
(d) Conditioning of slabs, blooms, or billets is done by grinding.
(e) Ingot scarfing.
(f) Selective grinding of billets.
(g) Selective scarfing of cold billets at several scarfing stations.
(h) To be replaced by wet electrostatic precipitators.

IV. CHARACTERIZATION OF EMISSIONS

The fume generated during a scarfing operation is predominantly iron oxide. No information is available pertaining to the size distribution of the emissions or specific chemical composition. It has been reported that the loss in yield for scarfing billets varies from 3 to 6 percent depending on the types of steel scarfed.[36] However, most of this loss is in the form of metal splatter rather than fume. Several factors that influence the amount of metal removed include: (1) speed of the semifinished product through the machine, (2) oxygen pressure at the scarfing head, (3) temperature of the steel, and (4) the chemical composition of the steel.[35, 37-40] Inlet and outlet dust loadings for several wet electrostatic precipitator installations are given in Table 3.[10, 22]

TABLE 3. SCARFING MACHINE WET ELECTROSTATIC PRECIPITATOR DUST LOADINGS

Type of Mill	Gas Flow		Inlet Loading		Outlet Loading	
	Nm^3/min	ACFM	grams/Nm^3	grains/SCFD	grams/Nm^3	grains/SCFD
Billet	643	22,700	2.0-48.0	0.50-3.00	0.028-0.029	0.0070-0.0073
Billet	1,032	36,400	1.329-2.528	0.332-0.631	0.009-0.057	0.0023-0.0143
Blooming	740	26,100	5206	1.3	0.015-0.047	0.0038-0.0117
Blooming	1,700	60,000	0.093-0.101	0.023-0.025	0.003-0.004	0.0008-0.0009
Slabbing	2,018	71,200	0.027-0.389	0.007-0.097	0.017-0.026	0.0042-0.0064
Slabbing	2,891	102,000	0.400-2.002	0.100-0.500	0.026-0.056	0.0065-0.0139

Nm^3/min - normal cubic meters per minute.
ACFM - actual cubic feet per minute.
SCFD - standard (normal) cubic feet, dry.
grain - 1/7000 pound.

V. SCARFING MACHINE WET ELECTROSTATIC PRECIPITATOR DESIGN CHARACTERISTICS

This section is concerned with design fundamentals for tube or pipe-type wet electrostatic precipitators and duct-type (i.e., those that use plates for collection) wet electrostatic precipitators. Dry electrostatic precipitators are not considered. Dry electrostatic precipitators have had severe corrosion problems and the trend is toward the use of wet electrostatic precipitators. Seven dry electrostatic precipitators are listed in operation in Table 1. Two of these installations are scheduled for replacement by wet electrostatic precipitators.[27] This will bring the number of wet electrostatic precipitators in operation to 14.

ELECTROSTATIC PRECIPITATOR PARTS*

The three basic parts of any precipitator installation are:

(1) Power supply
(2) Collection area
(3) Dust-removal area.

The power supply generally consists of a single-phase, high-voltage transformer, appropriate control equipment, and a bridge rectifier circuit. The rectifier circuit can be either a full-wave or double half-wave circuit, as shown in Figure 1.

Rectifier design has progressed from the mechanical rectifier to the high-voltage Kenotron vacuum tube, selenium, or silicon rectifiers. Normal transformer ratings are between 15 and 25-kva, 440-volt primary and 50 to 75-kv secondary. To limit short-circuit current surges, the transformer primary circuit usually contains a ballast

* Reprinted from Iron and Steel Engineer. Electrostatic Precipitator Primer. J. Katz, by permission of the Association of Iron and Steel Engineers. pp. 21-40, May 1964.

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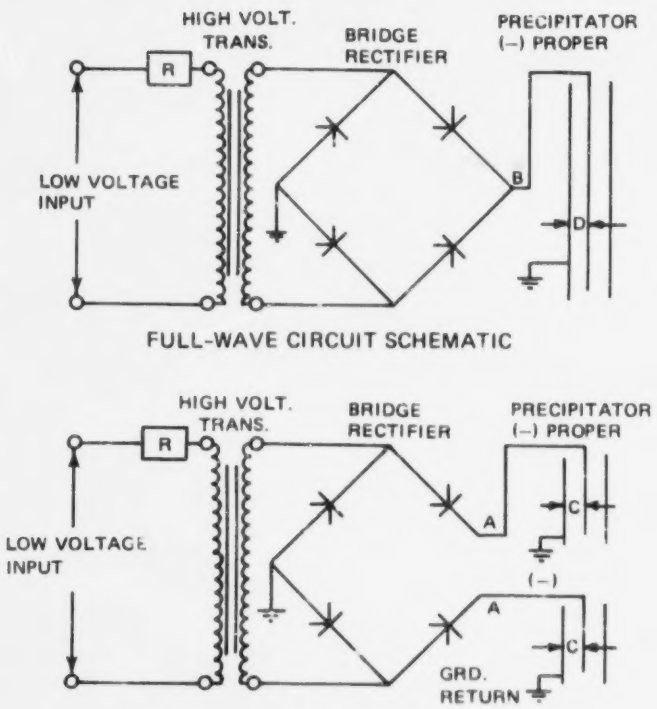

Figure 1. Two types of rectifier circuits for an electrostatic precipitator

resistance or a reactor. Manual or automatic control is used to regulate electrical conditions in the precipitator dust-collection area.

The collection area consists of either ducts or pipes with high-voltage discharge electrodes uniformly spaced and of uniform length, as illustrated in Figures 2 and 3. Collecting electrodes (the metal surfaces that collect the particles) are at ground potential and are connected directly to the frame of the precipitator. The collecting-surface design varies with the manufacturing company and process. The collecting surface of ducts may consist of perforated or solid metal plates up to 1.4 x 6.0 meters (4.5 x 20 feet). Normally a precipitator has three to four duct sections in series. The duct width may be 200 mm (8 inches), although 250 mm (10 inches) ducts are sometimes employed in cleaning gases that contain large quantities of dust. There can be five or six discharge electrodes equally spaced

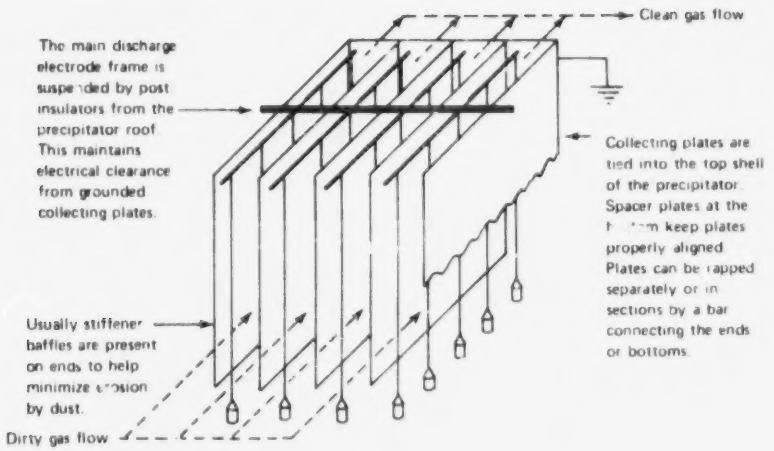
Clean gas flow
The main discharge electrode frame is suspended by post insulators from the precipitator roof. This maintains electrical clearance from grounded collecting plates.
Collecting plates are tied into the top shell of the precipitator. Spacer plates at the bottom keep plates properly aligned. Plates can be rapped separately or in sections by a bar connecting the ends or bottoms.
Usually stiffener baffles are present on ends to help minimize erosion by dust.
Dirty gas flow

Figure 2. Typical duct-type electrostatic precipitator

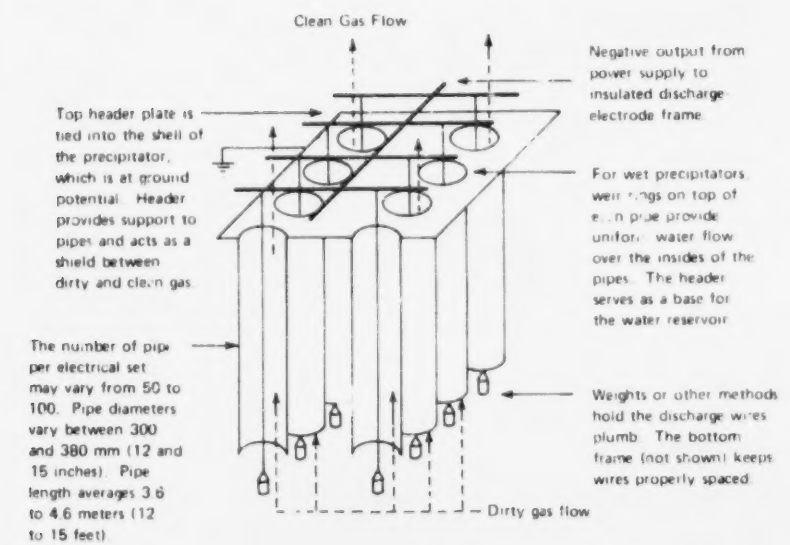
Clean Gas Flow
Negative output from power supply to insulated discharge electrode frame.
Top header plate is tied into the shell of the precipitator, which is at ground potential. Header provides support to pipes and acts as a shield between dirty and clean gas.
For wet precipitators, weir rings on top of each pipe provide uniform water flow over the insides of the pipes. The header serves as a base for the water reservoir.
The number of pipe per electrical set may vary from 50 to 100. Pipe diameters vary between 300 and 380 mm (12 and 15 inches). Pipe length averages 3.6 to 4.6 meters (12 to 15 feet).
Weights or other methods hold the discharge wires plumb. The bottom frame (not shown) keeps wires properly spaced.
Dirty gas flow

Figure 3. Typical pipe-type electrostatic precipitator

in each 1.4-meter (4.5-foot) duct section. These discharge electrodes receive the high-voltage rectifier output and are suspended in parallel from a framework that is insulated from ground by ceramic insulators.

Pipe-type collecting units are normally used for cleaning blast-furnace gas, removing tar from coke-oven gas, cleaning scarfing-machine emissions, and in recent years have been considered for cleaning reclamation (sinter) plant emissions. Pipe units differ from duct units primarily in having only one discharge electrode for each collecting electrode; duct units have several discharge electrodes in each duct. (See Figures 2 and 3.)

Both pipe-type and duct-type wet precipitators normally use water flowing over the collecting surfaces to flush the emissions from the collecting surfaces. The practice for wet electrostatic precipitators on scarfing operations is to flush the collecting surfaces periodically after a given number of slabs, blooms, or billets have been scarfed. The flushing period is influenced by the kind of semifinished product, the type of steel, and the amount of steel removed during the scarfing operation.

WET ELECTROSTATIC PRECIPITATOR

The use of wet electrostatic precipitators for control of emissions from industrial sources was generally restricted to rather specialized applications such as on acid mist, coke-oven off-gas, blast furnaces, and detarring applications. The method of cleaning was in most cases intermittent and of the wetted-wall type.

As a result of much more stringent local, state, and Federal emission regulations, condensable materials were added to the total particulate loading. The removal of organic condensables, which are very difficult to wet and which form small droplets in the 0.1 to 2-micron range, requires scrubber pressure drops in the range from 1000 to 1500kg/m^2 (40 to 60 inches of water gage). Because the wet electrostatic precipitator is always operated at saturation temperature (100 percent relative humidity), it will remove organic materials with a condensation temperature higher than or equal to the gas saturation temperature. It will also remove solid dust particles in the submicron range and gaseous contaminants soluble in the spraying liquor. Emissions are removed with very low energy consumption and a pressure drop usually less than 13 kg/m^2 (0.5 inches of water gage). The electric power input through the high-voltage power supplies is quite low, from 14 to 23 kw/m^3/min (0.5 to 0.8 kw/1,000 actual ft^3/min).

The recent development of a continuously sprayed, parallel plate, frame electrode and horizontal flow design has provided industry with a realistic alternative to high-energy scrubbers. The theory of operation, description of the design, and the power consumption are discussed in the following sections.

Wet-Dust-Collection Fundamentals[55]

The corona generation and the charging and discharging processes in the wet electrostatic precipitator are, in general terms, similar to what takes place in a conventional dry electrostatic precipitator except for some important differences.

Because the gas in the wet precipitator is always saturated with water vapor, the current and voltage relationship is somewhat different from that in the dry precipitator. With increasing amounts of water vapor, the spark-over voltage increases (i.e., the voltage at which the field breaks down), but the corona current at a given voltage is lower. When solid particles and droplets enter the electrostatic field, they will cause a local distortion of the electrostatic field between the electrode and the collecting plate. Some of the electric-field lines intersect the particles, and ions generated by the corona discharge will tend to travel along lines of maximum voltage gradient or along the field lines; therefore, some of the ions will collide with the particles and the charge gradually builds up on the particles.

This process continues until the charge on the particles is so high that it diverts the electric-field lines away from the charged particles, preventing new ions from colliding with the dust particles. When this state has been reached, the particles are said to be saturated with charge. Theory shows that the saturation charge value and charging time are dependent upon electric-field strength, size of the particle, the dielectric constant of the particle, and the relative position of the particle in the field. This charging process is said to be field dependent and is the dominant process down to a particle size of 0.2 μm. For smaller particles, the so-called diffusion charging process is the dominant mechanism; this is governed by the random thermal motion of the ions and is not limited to a saturation charge.

As soon as the charging process of the particle starts, the resulting electrostatic force will pull the particle toward the collecting plate. This force, together with the gravitational and the drag forces, and the gas-flow distribution in the field determine the particle trajectory and its point of collection.

In a dry electrostatic precipitator, the dust buildup on the collecting plate limits the maximum voltage at which the precipitator can operate. For dust layers with high resistivity (greater than 2×10^{10} ohm-cm) the voltage drop can be from 10 to 20 kv. This condition lowers the field strength in the space between the electrode and the dust deposit surface, and results in a lower saturation charge, which again gives a lower electrostatic force. If, on the other hand, the resistivity of the dust layer is lower than 10^7 ohm-cm, the electrostatic force holding the dust particle on the plates is low, and reentrainment can become a serious problem during the electrode- and plate-cleaning (rapping) cycle and also during the steady operation, having the overall effect of lowering the precipitator collection efficiency.

For a continuously sprayed wet electrostatic precipitator, the previously discussed problems are nonexistent. The spray liquid drops form a film on the collecting plates which continuously washes off the dust that is being collected. The resistivity of the liquid film is the governing factor in the dust-discharging process and not the resistivity of the dust layer itself. Reentrainment problems are also nonexistent, because the collected particles are instantaneously and continuously removed from the point of collection and are washed down as a light slurry. The exit loading is, therefore, much more stable and does not have the characteristic sharp increase that the dry electrostatic precipitator has during the collection-plate- and electrode-rapping cycles.

Therefore, for a wet electrostatic precipitator, the operation is not influenced by the resistivity of the dust layer. The major parameters that must be considered are the particles' dielectric constant and size.

To better understand the effect of low dielectric constants on horizontal migration distance of the particle, a mathematical model of the particle collection mechanism was developed. The analysis was based upon a field-charging process and a particle or droplet which had to traverse the whole net field spacing (one half of the plate-to-plate spacing). Particles of different sizes with dielectric constants of 2, 10, and 78 were investigated.

The unit consisted of parallel collecting plates with a separation of 2r. The velocity profile between the plates was assumed to be flat (plug flow) and turbulent drag forces were neglected. Centered between two plates was an electrode frame, with electrode spacing assumed sufficiently close to provide an approximately uniform electrostatic field near the plate surface. The field strength was approximately 70 percent of the field that was to be produced by a solid discharge-plate electrode, or

$$E = -0.70\, dv/dr. \tag{1}$$

The nomenclature for the equations is given in Table 4.

The current density under no-load condition will be

$$J = i/A_c. \tag{2}$$

The ionic space charge can be determined from the current density – electric field equation:

$$J = N_o e \mu_i \overline{E} \quad (\overline{E} = \text{mean electrostatic field strength}). \tag{3}$$

The saturation charge for a nonconductive particle is

$$q_s = 12 \frac{\epsilon}{\epsilon+2} \pi \epsilon_o a_d^2 E. \tag{4}$$

The relative dielectric constant, ϵ, for a conducting particle approaches infinity and is equal to one for a perfect insulator.

The expression for the charge as a function of time is

$$q(t) = q_s \frac{t}{t+\tau}, \tag{5}$$

where τ is a charging time constant or

$$\tau = 4\epsilon_o/N_o e \mu \tag{6}$$

The particle-size range examined is larger than 0.2 μm, so the diffusion charge can be omitted.

If we start with a particle entering the field halfway between two plates and without any charge, the force balance is divided into three different components:

x - axis, the direction of the electrostatic field (transverse to gas flow)

y - axis, the direction of the gravitation force (vertically down)

z - axis, the direction of the gas flow (horizontal and axial).

TABLE 4. NOMENCLATURE FOR WET-DUST-COLLECTION FUNDAMENTALS

A	=	$6\pi a\eta/m$ = constant
A_c	=	Collection area
a_d	=	Particle diameter
B	=	$q_s E/m$ = constant
c_i	=	Particle inlet loading
c_o	=	Particle outlet loading
E	=	Electrostatic field strength
e	=	Electric charge
F	=	Force
g	=	Gravitational constant
i	=	Current
J	=	Current density
ln	=	Natural logarithm
m	=	Particle mass
N_o	=	Number density of free ions
V	=	Gas flow rate
q	=	Charge
q_s	=	Saturation charge
r	=	Net field spacing
s_x	=	Transverse distance
s_z	=	Horizontal distance
T	=	Migration time for collection
t	=	Time
v	=	Voltage
w	=	Velocity
w_{gas}	=	Gas average velocity
w_x	=	Transverse particle velocity
w_z	=	Horizontal particle velocity
x	=	Transverse horizontal distance
y	=	Vertical distance
z	=	Horizontal axial distance
ϵ	=	Dielectric constant
ϵ_o	=	Permittivity of free space
ϑ	=	Viscosity of gas
η	=	Collection efficiency
μ_i	=	Carrier mobility of the gas
π	=	3.1416
τ	=	Charging time constant
ω	=	Migration velocity parameter

The force balance is then as follows:

$$\Sigma F_x = F_{qe} - F_x - F_{ix} = 0 \tag{7}$$

$$\Sigma F_y = F_g - F_{\eta y} - F_{iy} = 0 \tag{8}$$

$$\Sigma F_z = F_{\eta z} - F_{iz} = 0 \, . \tag{9}$$

The electrostatic force can be expressed as

$$F_{qe} = qE \, . \tag{10}$$

Substituting Equations (1), (4), and (5) in Equation (10) gives

$$F_{qe} = 12 \frac{\epsilon}{\epsilon+2} \pi \epsilon \, a_d^2 \frac{t}{t + \frac{4\epsilon_o}{N_o e \mu}} \left(\frac{dv}{dr}\right)^2 0.49 \, , \tag{11}$$

which shows the influence of the dielectric constant, the particle size, and the field strength on the electrostatic force.

The gravitational force is

$$F_g = mg \, . \tag{12}$$

The viscous force, assuming Stoke's Law applies (laminar flow), is

$$F_\eta = 6\pi a_d \theta w \quad , \tag{13}$$

and the inertia force can be expressed as

$$F_i = m \, dw/dt \, . \tag{14}$$

If we assume that a spherical particle with a radius a is moving in this field, it will be charged to carry an amount of g (coul) charges, and the force balance in the transverse direction, after substituting Equations (10), (13), and (14) in Equation (7), becomes:

$$qE = 6\pi a_d \eta w_x - m \, dw_x/dt = 0 \, . \tag{15}$$

Substituting Equation (5) into Equation (15) gives

$$q_s \frac{t}{t+\tau} E - 6\pi a_d \theta w_x = m \frac{dw_x}{dt} ; \qquad (16)$$

let

$$A = 6\pi a_d \theta / m \text{ and } B = q_s E/m . \qquad (17)$$

Substituting this in Equation (16) and integrating gives

$$w_x = \frac{B}{A} - B\tau e^{-At} \int_0^T \frac{e^{-At}}{t+\tau} dt + C_1 e^{-At} . \qquad (18)$$

The term $\int \frac{e^{-At}}{t+\tau} dt$ cannot be integrated but can be approximated using a series solution:

$$\int \frac{e^{-a_d x}}{b+x} dx = e^{-a_d b} \left[\ln (b+x) + \sum_{n=1}^{\infty} [a_d (b+x)]^n / n \cdot n ! \right] .$$

Then, by using this expression in Equation (18) and integrating it once more with the following initial conditions

$$t = 0, \; w_x = w_{xo} = 0 \text{ and } s_x = s_{xo} = 0 ,$$

the travel distance s_x becomes

$$s_x = \int_0^T w_x dt = \frac{B}{A} \left(t - \frac{1}{A} (1 - e^{-At}) \right) + \tau e^{-A(t+\tau)}$$

$$\cdot \left[\ln \frac{t+\tau}{\tau} + \sum_{n=1}^{\infty} [(A(t+\tau)]^n - (A\tau)^n) / n \cdot n ! \right] - \tau \ln \frac{t+\tau}{\tau} . \qquad (19)$$

The migration distance is from 0 to 150 mm (0 to 6 inches), and the migration time, T, needed for the particle to be collected can then be found for s_x = 150 mm (6 inches) by a trial-and-error solution of Equation (19).

In order to obtain the horizontal distance needed for the particles to be collected, the force balance in the z direction must be considered, i.e., Equation (8). This expression becomes

$$6\pi a_d \theta \, (w_{gas} - w_z) = m \, dw_z/dt \, , \tag{20}$$

where $(w_{gas} - w_z)$ is the relative velocity between the particle and the gas. Integrating Equation (20), using the constants given by Equation (17) gives

$$w_z = w_{gas} \left(1 - e^{-At}\right) + w_{zo} e^{-At} \, , \tag{21}$$

where w_{zo} is the initial particle velocity along the z-axis. The horizontal travel distance becomes, then,

$$s_z = \int_o^T w_z dt = w_{gas} \left[t + \frac{1}{A} \; e^{-At} - 1 \right] - \frac{1}{A} w_{zo} \; e^{-At} - 1 \, . \tag{22}$$

Then, by using the travel time calculated from Equation (17), the horizontal traveling distance can be calculated as a function of particle (droplet) size and dielectric constant. With two 5-μm particles or condensed droplets, one with a dielectric constant of 2 (e.g., a condensed hydrocarbon droplet) and one with a dielectric constant of 78 (e.g., pure water droplet), migration across a field spacing of 150 mm (6 inches) with an applied voltage of 50 kv and a gas velocity of 0.9 m/sec (3 fps) will take a horizontal distance of 2.2 m (7.2 ft) and 1.2 m (3.9 ft), respectively. Therefore, the low-dielectric particle takes almost twice the horizontal distance before being collected. This analysis points to the fact that condensable hydrocarbons (tars) and other materials with a low dielectric constant will be much more difficult to collect than conductive particles, and this has been confirmed by measurements.

When considering the removal of condensable hydrocarbons (tar mist), it should be remembered that the dielectric constants for petroleum distillates are quite low (i.e., around 2). For example, hexane (C_6H_{14}) has a dielectric constant of 2 and a boiling point of 69 C (156 F), toluene (C_7H_8) has a dielectric constant of 2.15 and a boiling point of 110 C (230 F), and naphthalene ($C_{10}H_8$) has a dielectric constant of 2.54 and a boiling point of 218 C (424 F). Other organic liquids like phenol formaldehyde resin have a dielectric constant of 6.6. Pure water has a dielectric constant of 78.

The removal efficiency of the wet electrostatic precipitator on a given gas and dust stream is a function of six basic parameters:

Collection Area
Operating Voltage
Discharge Current
Liquid-to-Gas Ratio
Treatment Time
Local Average Velocity.

The performance is often stated by the so-called migration velocity. The higher the migration velocity is, the better the particulate removal efficiency or the smaller the wet electrostatic precipitator in terms of collection area needed to treat the gas flow. The relationship between migration velocity and wet electrostatic precipitator performance is given below.

$$\omega = -V/A\ 0.508\ \ln (c_o/c_i)\ . \tag{23}$$

The efficiency of the unit is given by

$$\eta = (1-c_o/c_i)\ 100\ , \tag{24}$$

and when substituting Equation (23),

$$\eta = (1-e^{(-Aw/0.508Q)})\ 100\ , \tag{25}$$

which is another expression for the Duetsch-Anderson Equation for precipitator efficiency:

$$\eta = 1 - e^{-\left(\frac{A_c w}{V}\right)}$$

The migration velocity ω is a performance parameter that does not in reality relate directly to the speed at which the particles migrate to the collecting plates. It is a "catch-all" which also includes all operating parameters not included in Equation (23).

HORIZONTAL-FLOW WET ELECTROSTATIC PRECIPITATOR

One of the wet electrostatic precipitators can be characterized as a continuously sprayed, horizontal-flow, parallel-plate, and solid-discharge electrode type. In terms of gaseous absorption, it can be characterized as a combination cocurrent and a cross-flow scrubber.

In the application of a wet electrostatic precipitator, it is very important that the gas to be treated is saturated with water vapor to prevent the water inside the wet electrostatic precipitator from evaporating, which causes loss of washing water and dry zones on the internal members. The saturation of the gas can be done in a spray tower or scrubber upstream of the wet electrostatic precipitator, or it can be done in the inlet section of the wet electrostatic precipitator, or both.

In addition, it is also necessary to obtain a uniform velocity profile across the wet electrostatic precipitator, and the diffusion of the flow from the inlet duct velocity down to the wet electrostatic precipitator face velocity has to be performed in the inlet section. Furthermore, by spraying cocurrent into the inlet section, some of the coarser particles will be removed and the gas-absorption process will be started. To accomplish this, sections of baffles and sprays are located in the inlet cone of the wet electrostatic precipitator.

After passing through the sections of transverse baffles, the dirty gas stream then enters into the first electrostatic field. Water sprays located above the electrostatic-field sections introduce the proper amount of water droplets to the gas stream for washing of internal surfaces. The particulates and the water droplets in the electrostatic field pick up a charge and migrate to the collecting plates. The collected water droplets form a continuous downward-flowing film over all the collecting plates and keep them clean. The water film and the collected particulates flow down the collecting plates into the troughs below, which are sloped to a drain.

The transverse-baffle gas-distribution system combined with the extended electrode, located upstream and downstream of each field, insures complete gas-flow uniformity from passage to passage, and collects particulates and droplets by impingement, and by electrostatic forces. Also, the extended discharge electrode system improves the collection efficiency by increasing effective collection area. At the entry of a field, particles not captured by the transverse baffles are given an

advance charge by the forward-extended electrode before they come into proximity of the collecting plates. Thus charged, the particles start immediately to migrate toward the leading edge of the plates. It has been found that the downstream side of the baffles at the exit of a field collects a considerable amount of material. The very small charged particles escaping the parallel-plate field are pulled into the wake of the baffles by the slight vacuum resulting from the turbulent dissipation of energy. Because the particles have an electrostatic charge, some of them will be collected on the back side of the baffles.

All baffles systems are arranged so that a walkway runs across the front and the back of each of the electrostatic fields. The discharge electrode frames are mounted on collar-type, high-voltage support insulators. Insulator compartments are heated and pressurized to prevent moisture and particulate leakage into the insulator compartment.

In any particulate and/or gaseous removal process where a liquid is used, it is important to remove the carryover liquid drops and mists before reaching the outlet of the equipment. It has been found that doing this electrostatically is highly efficient. Hence, the last section is operated dry, thereby establishing an electrostatic barrier that the liquid droplets cannot penetrate. The mist collects on the front side of the baffles, and the downstream side is dry. However, some small dust particles can penetrate and these will collect on the downstream baffles. Therefore, this surface is washed intermittently to prevent buildup of particulates.

RANGE OF APPLICATIONS

During the past 2 years, many new applications have been piloted and units have been sold and installed following successful pilot-plant work. The wet electrostatic precipitator can be used for applications on gas streams containing relatively light dust loading of submicron particles and/or condensed organic materials forming a submicron fume. Ordinarily these applications would require very-high-pressure-drop scrubbers. The energy consumption and operating costs are less than what would be needed to operate scrubbers. The water-treatment requirements for the wet electrostatic precipitator are about the same as those for scrubbers.

In some applications, where the dust resistivity is either very high or very low, the wet electrostatic precipitator can also be applied successfully in competition with dry electrostatic precipitators.

Scarfer Wet Electrostatic Precipitator Design Data

There is no information in the published literature pertaining to the design and operating data of scarfing machine wet electrostatic precipitators. Table 5 presents data supplied by some steel companies for wet electrostatic precipitators installed at their steel plants in the United States.[22, 27]

There is no published information pertaining to the size distribution of scarfer emissions or their chemical compositions. This type of information is not available from any steel companies in the United States.

Table 6 presents data on the operating design conditions and test results for three scarfing wet electrostatic precipitators.[9] These data were obtained by the steel plants to verify the performance of the precipitators.

No major operating or maintenance problems were reported during start-up and operation of the wet electrostatic precipitators installed on the 762 533-mm (30 21-inch) billet mill and the 1016-mm (40-inch) blooming mill. About three years after the wet electrostatic precipitator was installed on the 1143 x 2286-mm (45 x 90 inch) slabbing mill, a reduction in exhaust capacity resulted in a reduction in the ability of the hood to capture fume at the scarfer. It was determined that the mist eliminator of the separator was becoming clogged and dirt buildup was taking place on the precipitator tubes. Clogging of the mist eliminator was resolved by removing approximately two thirds of the flex rings in the mist eliminator bed and washing down the remaining rings and bed area. The buildup of dirt on the precipitator tubes was eliminated by more frequent flushing of the modules. Originally a module was flushed after every ten scarfs. This was reduced to flushing after every three scarfs.[9]

Operating and maintenance costs in 1974, for the 1016-mm (40 inch) blooming mill and 1143 x 2286-mm (45 x 90 inch) slabbing mill, were reported to be $0.009 per tonne ($0.01 per net ton) or less. This cost did not include the cost to operate and maintain the exhaust fans which were a part of the original equipment before installation of the wet electrostatic precipitators.[9]

TABLE 5. DESIGN CHARACTERISTICS AND OPERATING CONDITIONS FOR SCARFING WET ELECTROSTATIC PRECIPITATORS

Item	18-inch Billet Mill		Blooming Mill		Slabbing Mill	
Gas volume	1,275 m^3/min	45,000 ACFM	2,125 m^3/min	75,000 ACFM	2,834 m^3/min	100,000 ACFM
Gas temperature	4-66 C	40-150 F	4-66 C	40-150 F	52 C	125 F
Pressure	<25 mm	< 1 inch	380 mm	-15 inches	12.7 mm	6 inches
Inlet dust loading	4.6 grams/m^3	2.0 grains/SCF	4.6 grams/m^3	2.0 grains/SCF		
Outlet dust loading	0.02 grams/m^3	0.01 grains/SCF	0.02 grams/m^3	0.01 grains/SCF	0.02 grams/m^3	0.01 grains/SCF
Number of precipitators	1		1		1	
Modules per precipitator	2		3		4	
Fields per chamber	1		1			
Discharge electrodes						
per module	96		96		84	
per precipitator	192		288		336	
Collecting surfaces						
per module	96		96		84	
per precipitator	192		288		336	
Collecting surface						
type	Tube		Tube		Tube	
material	Stainless steel		Stainless steel		Stainless steel	
diameter	25.4 cm	10 inches	25.4 cm	10 inches	25.4 cm	10 inches
length	4.6 m	15 feet	4.6 m	15 feet	4.6 m	15 feet
Reactor rating	42 KVA					
Transformer-rectifier						
type	Silicon		Silicon			
KVA			60		60	
MA			400		1,200	
dielectric			Askarel			
Power source						
Volts	460		460			
Hz	60		60			
Phases	3		3			
Insulator compartment ventilation	Forced draft, electrically heated					

ACFM = Actual cubic feet per minute. Grain = 1/7000 pound. SCF = Standard cubic foot.

TABLE 6. DESIGN OPERATING CONDITIONS AND TEST RESULTS FOR SCARFING WET ELECTROSTATIC PRECIPITATORS

Item	762 x 533 mm (30 x 21 inch) Billet Mill		1016 mm (40 inch) Blooming Mill		1143 x 2286 mm (45 x 90 inch) Slabbing Mill	
Design Operating Conditions						
Gas volume	736 m^3/min	26,000 ACFM	708 m^3/min	25,000 ACFM	4,248 m^3/min	150,000 ACFM
Gas temperature	10-66 C	50-150 F	52 C	125 F	38-66 C	100-150 F
Moisture content	Saturated		5 percent		2-10 percent	
Average gas inlet loading	3.43 grams/m^3	1.50 grains/SCFD	2.98 grams/m^3	1.30 grains/SCFD	0.23 grams/m^3	0.30 grains/SCFD
Average gas outlet loading	0.07 grams/m^3	0.03 grains/SCFD	0.07 grams/m^3	0.03 grains/SCFD	0.07 grams/m^3	0.03 grains/SCFD
Test Results						
Gas volume	643 m^3/min	22,700 ACFM	739 m^3/min	26,100 ACFM	2,889 m^3/min	102,000 ACFM
Gas temperature	24 C	75 F	46 C	115 F	33 C	91 F
Moisture content	5.5 percent		2.1 percent		4.6 percent	
Average gas outlet loading	0.016 grams/m^3	0.007 grains/SCFD	0.019 grams/m^3	0.008 grains/SCFD	0.023 grams/m^3	0.010 grains/SCFD
Scarfing rate	81 tonne/hr	89 net tons/hr	152 tonne/hr	168 net tons/hr	428 tonne/hr	472 net tons/hr

ACFM - Actual cubic feet per minute.
Grain = 1/7000 pound.
SCFD - Standard cubic foot (dry).

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